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Finite -Element Thermal Analysis of Thermal Bridge of Vacuum Insulation Panels Based on Temperature-Dependent Laminate Properties

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Abstract

Vacuum Insulation Panels(VIPs) have been regarded as a super thermal insulating material with high efficiency. In order to enhance the ability of the barrier material, which is used as the envelope in VIPs, to resist the permeation of water vapor and gases through it, aluminum is used in the laminate, thus thermal bridge is triggered due to the much higher thermal conductivity of Al compared with that of the core material. In this study, accounting for the temperature dependent thermal conductivity of different materials in the envelope, thermal flux of each layer was calculated through a two -dimensional nonlinear steady-state heat transfer model by Finite Element Method(FEM). The relationship between thermal flux of each layer in the envelope with different temperature differences between the warm and cold side of the VIP was presented, which could provide theoretical basis to optimize each layer.

Keywords: Vacuum insulation panel; thermal bridge; thermal analysis; laminate

1. Introduction

The "vacuum insulation panel" (VIP) is typically made of a micro-porous core structure which is evacuated and sealed in a thin mostly gas tight envelope. Due to its satisfactory insulation quality, a VIP of only 20mm can therefore replace a conventional mineral wool or PU-foam insulation board of 185 or 120mm respectively[1].

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Besides, the Ozone Depletion Substance(ODS) is not used in the process of VIP producing and application, which is profitable to protect the environment. So, the VIPs have been used attractively in thermal insulation fields.

The vacuum inside VIPs is vital to reduce the thermal conductivity of the product[2]. To maintain the vacuum inside the core material for a period as long as possible (at least 25 years but preferably 50 years for architectural applications), a barrier material with lower water vapor and gas permeance is required. At present, the laminated aluminum foils(AF) or aluminium-coated multilayered foils(MF) can meet the above requirements, which were shown in Figure 1[3]. However, Vacuum Insulation Panels typically exhibit an edge effect due to the high thermal conductivity of aluminium (225W/(m K)) compared to the conductivity of the core (0.004 W/ (m.K) in dry condition) and the polymer layers (0.25–0.30 W /m K). As the aluminium layer surrounds the core completely, there is an additional heat loss through the edge (fringe) of the panel (Figure 2).

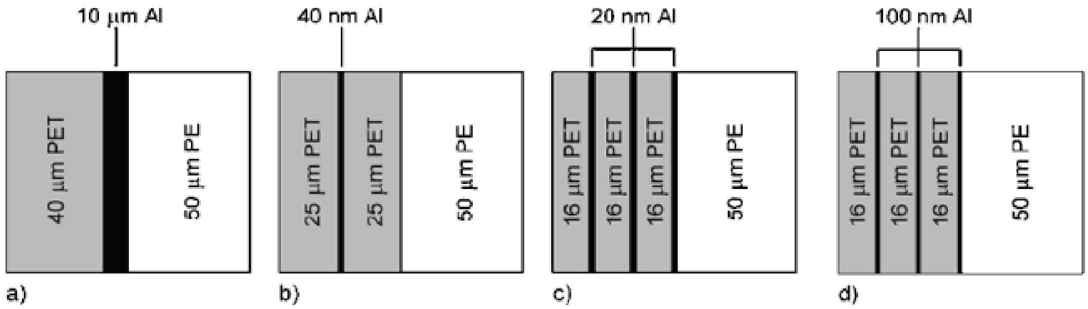

Figure 1 . Schematic view of foils used in VIPs

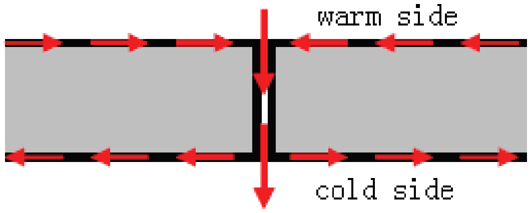

Figure 2 The diagram of thermal bridge

Several investigations about the thermal bridge of VIPs have been increasingly and deeply performed. The thermal bridge effect was investigated by K.Ghazi Wakili[4], Hubert Schwab[5]and Annex39[6]making use of both measurement with the guarded hot plate and numerical analysis of the thermal and temperature field; Martin Tenpierik[1] used analytical models for calculating thermal shunting of the high barrier laminates caused by the panel size, the foil (particularly the laminated Al foils), the air gaps or foam fillings between adjacent VIPs. S. Brunner[7]conducted the thickness analysis of the aluminum layers of two types laminates by means of the focused ion beam (FIB) etching method. Kuninari Arakia[8]optimize the laminates and gas absorber under ultra high temperature according to the thermal bridge effect.

Based upon these references, there are many methods to reduce the thermal bridge effect including increasing the size and the thickness of the VIP, reducing the thermal conductivity of laminates. However, in the researches described above, it is assumed that the material in the foil of VIP is homogeneous and has a constant thermal conductivity. This don't accord with the layered structure in the envelope of VIP. In addition, how to optimize each layer of the laminate has not been considered. This study therefore presents two -dimensional nonlinear steady-state heat transfer model for calculating the thermal flux of each layer under different temperature differences between the warm and cold side of the VIP, accounting for the temperature dependent thermal conductivity of different materials in the envelope, which could provide theoretical basis to optimize each layer.

2. Numerical calculation method

2.1The geometric model

The finite element program ANSYS was used to calculate the heat flows and temperature fields of the VIP in two dimensions. The accurate of the analytical results depends on the geometric model and the mesh accuracy. In fact, it is difficult to get very fine grid for the large difference of the thickness between the laminates and the core material. Based on it, several parameters need to be specified (Figure 3):

(1) the size of the panel is chosen to be 200mm*200mm*10mm;
(2) the AF laminates was schematized as three layers : PE 50μm, AL 10μm, PET 50μm;
(3) since the panel is symmetrical, half of the panel is chosen to establish the heat transfer model;
(4) The effect of the getter and the gas gap is not considered.

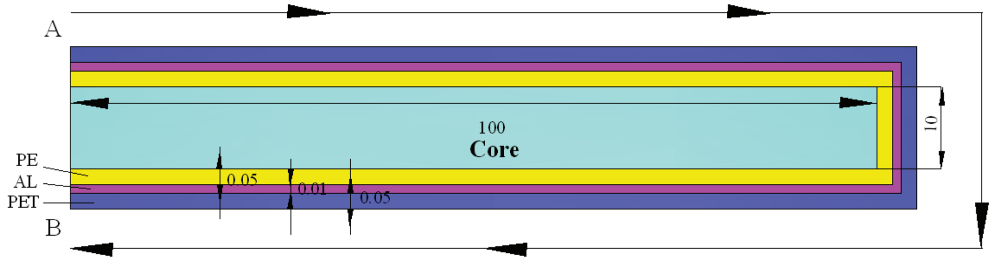

Figure 3 The geometric model of a VIP (not scaled, the unit is mm)

2.2 The mathematical model

In the past numerical simulation references, the thermal transmit of the VIP is usually calculated by the method of linear thermal analysis, in which the thermal conductivity of the laminate was assumed to be constant. In fact, when the temperature is low or high enough, the thermal conductivity of some laminate materials could strongly affected by temperature.

As a result, the numerical analysis was carried out by means of the ANSYS program by calculating two-dimensional nonlinear steady heat transfer in objects, described in a rectangular PLAN55 grid using the energy balance technique according to equation (1).

$$\{q\}=\begin{Bmatrix} q_x \\ q_y \end{Bmatrix}=([k]+[k(T)])\{T_g\} \tag{1}$$

{q}is the overall thermal flux, $\{T_g\}$ is the temperature ,{[k]+[k(T)]}is the conduction matrix including the thermal conductivity and the surface heat transfer coefficient. k(T) is the conduction matrix affected by temperatures.

2.3 Thermal parameters and boundary condition

Thermal conductivity values of the barrier materials used in the thermal analysis was presented in Table 1[9,10]. Due to the heat transmit between the sides of the VIP and the surrounding air is a convective heat transfer process, the boundary condition meets with the equation (2).

$$-\mathrm{K}\frac{\partial \mathrm{T}}{\partial n}\Big|_s=\alpha(T-T_f) \tag{2}$$

T_f is the temperature of the surrounding temperature, the heat transfer coefficient α at the interior and the external side of VIP is 5w/m^2.k.

Table 1 Thermal conductivity of the barrier material （W/mK ）

material \ T（℃）	−50	0	20	50
PE	0. 31	0. 32	0. 35	0. 38
AL	225	225	225	225
PET	0. 19	0. 22	0. 23	0. 24

3. Results and analysis

3.1 The calculation of the thermal bridge effect

The thermal bridge effect can be characterized by the linear thermal transmittance Ψ which can be calculated by the equation (3) and (4)[11,12].

$$\mathrm{U_{eff}} = U_{cop} + \frac{l_p}{s_p}\varphi_{vip,edge} \tag{3}$$

$$\mathrm{U_{cop}} = \left\{\frac{1}{\alpha_{in}} + \frac{d_p}{\lambda_{cop}} + \frac{1}{\alpha_{out}}\right\}^{-1} \tag{4}$$

Where, U_{eff} (W/m^2.K) is overall thermal conductance; U_{cop}(W/m^2.K) is the center-of-panel thermal conductance without considering the thermal bridge effect; α_{in} and α_{out} (W/m^2.K) are the surface heat transfer coefficients on the inside and the outside of the VIP respectively; l_p (m) is the panel circumference; S_p (m^2) is the panel surface area; λ_{cop} (W/m.K) is the center-of –panel thermal conductivity; d_p (m) is the thickness of VIP; $\varphi_{vip,edge}$ is the linear thermal transmittance(W/mK).

The equations pointed that the overall thermal conductance is proportional to the value of the linear thermal transmittance when the U_{cop} is assumed to be constant. So the overall thermal conductance can be used to evaluate the thermal bridge effect. In this paper, the thermal bridge effect of every laminate layer is expressed by the relation graph between the thermal flux and the thermal flow path. The path starts from the centre of the warm side of the panel (A), along with the direction of the thermal flow, as shown in Figure3, finally ends in the cold side of the panel(B). So, the thermal flux at the path range of 0mm~50mm, 200mm~260mm can represent the thermal bridge effect of the laminate at the centre of the panel, and the effect at the edge of the panel is reflected by the thermal flux at the path range of 100mm~130mm. In the graph, the value of the path is used as coordinate axis X , and the thermal flux is used as coordinate axis Y(the path length is according to the heat flow along the grid used in Ansys).

3.2 The influence of the temperature difference

When the vacuum insulation panel is used in fields with different temperature differences, thermal bridge will be obviously different. In order to find the measures to improve laminates to adapt to the different temperatures, the thermal analysis is conducted for three layers including the PE, AL and PET. For each layer, four different conditions of the temperature differences between warm side and cold side have been investigated: 10℃, 30℃, 50℃, 80℃.

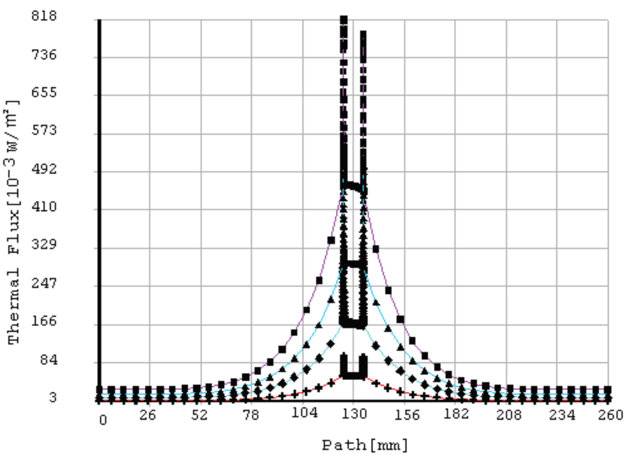

Figure 4 Thermal flux of the PE layer under different temperature difference between the both sides of VIP (■-ΔT 80℃,▲-ΔT 50℃, ◆-ΔT 30℃, ✚ -ΔT 10℃)

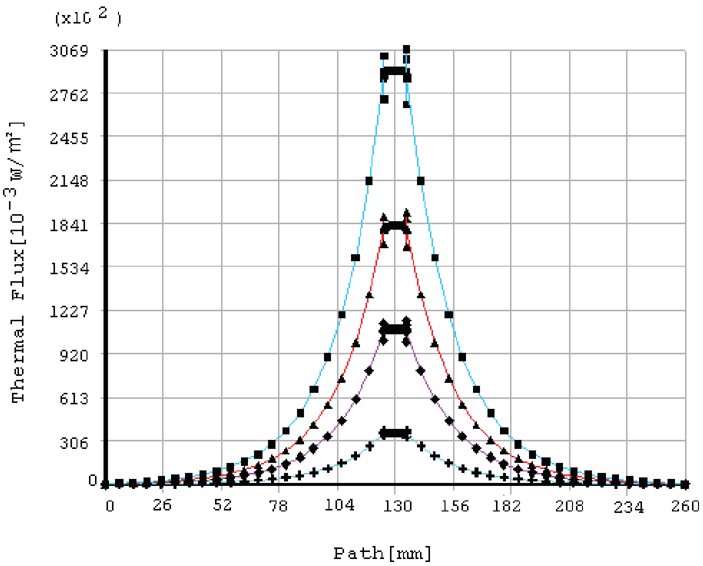

Figure 5 Thermal flux of the AL layer under different temperature difference between the both sides of VIP
(■-ΔT 80℃,▲-ΔT 50℃, ◆-ΔT 30℃, ✚ -ΔT 10℃)

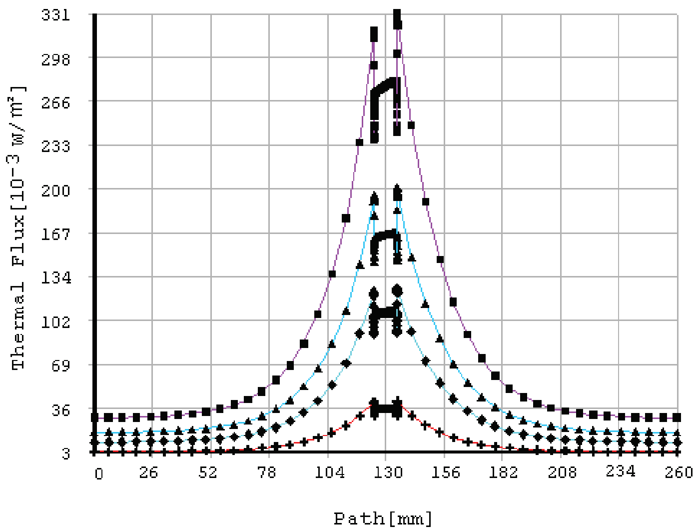

Figure 6. Thermal flux of the PET layer under different temperature difference between the both sides of VIP
(■-ΔT 80℃,▲-ΔT 50℃, ◆-ΔT 30℃, ✚ -ΔT 10℃)

The Figs. 4-6 show that:

(1) The thermal flux of the three layers(PE, AL, PET) in the path range of 0mm~50mm and 200mm~260mm is below 0.003W/m^2. In contrast, the thermal flux is high to 10~10^3 order of magnitude at the edges. Therefore, the effect of the thermal bridge on the thermal flux at the edge of the VIP is much larger than that at the center of the panel, and it can reach the maximum at the corner.

(2) By comparing the thermal flux on the same value of the path under different temperature difference, it can be seen that the thermal flux flowed through every laminate increases with the temperature difference increasing. Besides, the enlargement is proportional to the degree of the effect of the thermal bridge on the thermal flux.

(3) The thermal bridge caused by the laminate is low at the path range of 0mm~50mm, 200mm~260mm. When the temperature difference increases from 10℃ to 80℃, the thermal flux of the AL layer is almost unchanged while the increasing extent of PE and PET layer is up to 10 times. When the path value range from 200mm to 260mm, the effect was in the order of AL>PE>PET. As a result, when the thermal bridge is low, the degree of the influence of

the temperature difference between warm side and cold side is mainly dependent on the change of thermal conductivity with the temperature. When the thermal bridge is high, the thermal conductivity plays an important role.

4. Conclusions and Outlook

Based on the researches above, it can be concluded that:

(1) The method of nonlinear analysis should be used to calculate thermal flux in the envelope when the temperature difference between warm side and cold side of the VIP is large.

(2) The temperature difference has a great effect on the thermal flux of each layer, so it is necessary to optimize the thermal bridge effect under different temperature differences.

(3) According to the reference, the thermal bridge effect is lower for the panel of large size. So , for the panel of large size, if the laminate material is chosen with a bit higher thermal conductivity and insensitive to temperature, not only is the ability of envelope to resist permeation enhanced, but also the effect of the temperature difference on the thermal bridge is diminished, which even can not increase the overall thermal flux.

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